Automatic multiscale approach for water networks partitioning into dynamic district metered areas

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Abstract Water distribution systems (WDSs) today are expected to continuously provide clean water while meeting users demand, and pressure requirements. To accomplish these targets is not an easy task due to extreme weather events, operative accidents and intentional attacks; as well as the progressive deterioration of the WDS assets. Therefore, water utilities should be ready to deal with a range of disruption scenarios such as abrupt variations on the water demand e.g. caused by pipe bursts or topological changes in the water network. This paper presents a novel methodology to automatically split a WDS into self-adapting district metered areas (DMAs) of different size in response to such scenarios. Complex Networks Theory is proposed for creating novel multiscale network layouts for a WDS. This makes it possible to automatically define the dynamic partitioning of WDSs to support further DMA aggregation / disaggregation operations. A real, already partitioned, water utility network shows the usefulness of an adaptive partitioning when the network is affected by an abnormal increase of the peak demand

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of up to 15%. The dynamic DMA reuses the assets of the static partitioning and, in this case, up to the 82% of resilience is restored by using 94% of the assets already installed. The results also show that the overall computational and economic management costs are reduced (compared to the static DMA partition) while simultaneously preserving the hydraulic performance of the WDS.

Keywords Water Distribution Systems · Complex Networks · Semi-supervised clustering · Dynamic operation and sustainable management · Abnormal conditions

1 Introduction

Climate change adaptation and population growth are stressors on water resources management and consequently water utilities face new challenges for the optimal operation and management of water distribution systems (WDSs). Therefore, in addition to supplying water to users and to achieving service level requirements, water utilities also need to manage ab- normal conditions (such as burst pipe scenarios and peak demand variability), to achieve optimal sensor station placement (Klise et al, 2013), leakage detection (Wu et al, 2016), and to resolve, at near real-time, accidental or intentional contamination (Grayman et al, 2009; Xin et al, 2017) and cyber-attacks (Housh and Ohar, 2018; Taormina and Galelli, 2018). Within this context, it is common practice for WDSs to be split into district metered areas (DMAs) (Water Industry Research Ltd., 1999). DMAs represent monitored sub-regions of the original WDS that are formed by placing gate valves and flow meters along the boundary pipes connecting each DMA to another. This management technique is called Water Network Partitioning (WNP), and it has become one of the most attractive and studied strategies for the improvement of WDS management (Charalambous, 2008). Over the years, working with DMAs has helped water utilities to simplify water balance computation (Ferrari et al, 2013), carry out leakage control (Taillefond and Wolkenhauer, 2002; Feng and Zhang, 2006; Azevedo and Saurin, 2018) pressure management and hydraulic performance (Water Industry Research Ltd., 1999), monitor water quality (Kirstein et al, 2014; Ciaponi et al, 2019), and speed up repair interventions (Scarpa et al, 2016). The smaller monitored areas reduce the complexity of the network layout, thereby making it possible to compare the overall WDS performance between DMAs. Hence, water utilities can more efficiently work with suitable operational and management programs.

Despite the fore-described advantages, the usual WDS partitioning into DMAs comes with a few inconveniences mainly related to energy efficiency and water quality. A dynamic approach to WNP represents a valid and efficient solution for dealing with these drawbacks (Wright et al, 2014a). This paper proposes a general framework for approaching such dynamic partitioning of WDSs to take advantage of managing and controlling WDSs by small discrete areas at certain hours (at night for leakage control (Farah and

Shahrour, 2017) or during water disruption scenarios, e.g.) while providing a more efficient supply at certain hours of the day (peak-demand hours, e.g.) given the new partitioning into bigger DMAs for regular supply.

The current proposal pioneers an automated and practical approach to effectively achieve the dynamic water network partitioning (DWNP) relative to an adaptive DMA configuration. This is settled by a novel multiscale abstraction of the original WDS layout. The process continues by approaching a clustering algorithm that considers the current DMA division. Consequently, the initial DMAs are:

1. *aggregated* into bigger areas by a clustering methodology that preserves the connectivity of the original WDS. This aims to preserve the network resilience, to improve the pressure management, and to ensure the water quality;
2. periodically *disaggregated* according to the specific objective of the water utilities (i.e. leakage monitoring at night).

Dynamic DMAs are basis of a generic framework for the top-down / bottom-up partitioning of a WDS towards a smart and efficient management in abnormal functioning conditions. Few works can be considered antecedents of this paper. In particular, the work of Wright et al (2014b, a) proved great advantageous when such dynamic approaches were applied for DMA based management in a water utility. However, these works only investigated the benefits of dynamic partitioning and fall short of providing a methodological approach for its actual delivery. The novelty of the current paper is not only to show the results but to demonstrate the efficacy of such WDS dynamic partitioning. A case-study based on a real water utility shows the suitability of the dynamic DMAs to achieve optimal results in terms of network resilience necessary to address the non-anticipated increase in peak demand.

2 Permanent water network partitioning

Commonly, a WNP is accomplished in two phases (Perelman et al, 2015):

1. *clustering* phase: for defining the shape and dimension of the network subsets, balancing the number of nodes for each cluster and minimising the number of boundary pipes N_{ec} through graph algorithms (Deuerlein, 2008; Perelman and Ostfeld, 2011), multilevel partitioning (Alvisi, 2015), multi-agent systems (Herrera et al, 2012), spectral approaches (Herrera et al, 2012), modularity-based procedure (Ciaponi et al, 2016)
2. *dividing* phase: for selecting the boundary pipes along which flow meters or gate valves to be inserted, minimising the economic investment and the hydraulic performance deterioration (Gomes et al, 2013), through an iterative approach (Ferrari et al, 2013), optimisation algorithms (Saldarriaga et al, 2019) and heuristic methodology (Pesantez et al, 2019).

The advantages of the WNP are:

- Improved leakage detection and identification;
- Simplified sub-area management;
- Improved protection against contaminant;
- Improved sub-area pressure control.

Despite the advantages on using permanent DMAs, some associated disadvantages should be considered during the WNP design due to the closure of a number of boundary pipes, which reduces WDSs connectivity redundancy and could lead to inefficient supply. Therefore, the main disadvantages are:

- Reduced resilience to failures;
- Reduced operational flexibility;
- Water issues in peripheral areas;
- Investment and maintenance costs.

Specifically, one of the main problems is the more partitioned the network, the more dissipated the energy of the water supply. This leads to lower water pressures at the end user (Wright et al, 2014b) and might deteriorate the hydraulic performance and reliability of the system (Herrera et al, 2016). Another issue with permanent DMAs is related to water ageing. Particularly, in low consumption network areas. This would require timed operational maneuvers such as opening boundary valves where stagnant water have been accumulated. Furthermore, an optimal WNP design is often approached by referring to the ordinary operational conditions which are based on a static representation of the system. This is not enough to face unexpected conditions that may compromise the system performance and spatio-temporal approaches should be considered (Di Nardo et al, 2018). This is the case of dealing with the occurrence of unplanned water demand peaks, insufficient pumping or storage capacity, or pipe breaks. Dynamic DMAs will search an optimal trade-off by maximising the benefits of an open WDS while still getting the advantages of managing and control a partitioned layout.

3 Dynamic water network partitioning

This section approaches the concept of dynamic water network partitioning (DWNP) through the novel concept of multiscale (MS) water network layout. This leads to a novel network visualisation in addition to a network preprocessing for automating the creation of dynamic districts using a semi-supervised clustering approach.

3.1 Multiscale network layout

The creation of a MS network layout starts with a network which is already divided into clusters or communities (DMAs for a WDS). Otherwise, an initial network division is proposed in the first instance. The key components of a MS network are the following:

- *single assets*: links and nodes representing generic elements of the original network: demand nodes, valves, junctions, pipes, tanks, reservoirs, and pump stations;
- *boundary nodes*: nodes acting as inlet / outlet of a network previously divided into discrete metered areas;
- *hyper-links*:
  - *boundary links*: links connecting boundary nodes belonging to different clusters or DMAs;
  - *internal links*: links connecting boundary nodes belonging to the same clusters or DMAs.

Boundary nodes provide essential information for grouping DMAs into bigger areas. They also maintain water supply control by tracking the DMAs inlets / outlets. Boundary nodes are connected between themselves by valves and pipes, represented as boundary links. The internal hyper-links represent the connectivity within each DMA. They are usually weighted by the strength of such DMA connection. Boundary nodes and hyper-links create a novel MS network with all the information necessary for grouping DMAs into bigger areas.

Many water utilities already work with WDSs divided into DMAs. These DMAs used to be of small sizes as they were designed for leakage control. This DMA size is no longer convenient as the objectives of a DMA-based water supply management extend to new challenges in recent years, . Therefore, dynamic DMAs create larger DMAs by dynamically grouping the existing ones. This is done by simply labelling the DMAs in the original WDS, and then reorganising these labels into a lower number of DMAs. This preliminary approach can be improved in a straightforward manner by using the MS network associated to the original WDS.

3.2 Semi-supervised clustering algorithm

Conventional clustering algorithms are unsupervised e.g. there are no previous information about the relationship between the elements to clustering. It is worth adopting semi-supervised clustering algorithms in addition to the values of the elements' features (Kulis et al, 2009). When preliminary information about the clusters are available (i.e. certain elements are known to belong to the same cluster (Bair, 2013)).

The DMA aggregation process is done by applying semi-supervised clustering overlaid on the MS network and by considering features such as the boundary nodes membership and internal DMA connectivity constraints. In this paper, the topology of the network and the key nodes of the MS network are considered in a semi-supervised clustering process lead to aggregate DMAs into bigger areas. The structural knowledge related to MS assets such as boundary nodes and pipes, e.g., comes in the form of pairwise must-link (boundary links) and cannot-link (internal links) constraints (Herrera et al, 2010). In this case, the algorithm must meet the following conditions:

– the new aggregate DMAs include the former districts without splitting them;
– any previous cluster layout and the devices already installed should be considered in the new, aggregated configuration;
– the set of new boundary links already belongs to the set of the boundary links of the original partitioning.

These hydraulic / structural features must be translated as constraint implementation in the MS clustering algorithm. They help to better manage the aggregation / disaggregation phases, minimise / nullify new investment costs and to reduce the computational burden of the whole procedure, providing an automatic, dynamic DMA configuration for a WDS.

This paper produces a novel MS network for WDSs. After the size reduction provided by the application of the MS algorithm, each cluster of the MS network becomes a fully connected layout with fewer links (*boundary links*) to each other. This topological property of the MS network assures that the clustering algorithm, applied for getting new bigger clusters, provides a solution in which the novel set of boundary links is a sub-set of the boundary links of the original cluster layout. Once the new MS network is settled, a network community detection algorithm (Girvan and Newman, 2002; Fortunato and Hric, 2016) splits the MS network to aggregate DMAs. Each new cluster is formed by elements having a high-density connection between each other in the MS network. According to this, the new cluster layout will certainly cross the former boundary links and will not split the original DMAs. A semi-supervised version of these clustering algorithms automatically considers the topological features of the MS network, automating the overall process.

3.3 Dividing phase

The clustering phase provides the size and shape of each cluster and the set of boundary links N_{ec} between clusters, i.e. the set of pipes along the installed (or to be installed) flow meters N_{fm} or gate valves. If N_{fm} is the number of flow meters, $N_{gv} = N_{ec} - N_{fm}$ corresponds to the number of gate valves (e.g. closed pipes). Generally, the main goal is to keep the number of flow meters N_{fm} as low as possible, to simplify the water budget computation (Di Nardo et al, 2018).

Since the number of possible dividing configurations is extremely high, the process run a heuristic optimisation approach to find the optimal position of flow meters and gate valves on the boundary links. In this case, a Genetic Algorithm (GA) (Goldberg and Holland, 1988) was developed and specifically tailored for the problem. The Objective Function (OF) in Equation (1) is maximised in Equation (1) which corresponds to the resilience index I_r of Todini (2000).

$$I_r = \frac{\sum_{i=1}^{n_n} Q_i(h_i - h^*)}{\sum_{r=1}^{n_r} Q_r H_r - \sum_{i=1}^{n_n} Q_i h^*} \qquad (1)$$

where n_n is the number of demand nodes, n_r is the number of reservoirs, Q_i and h_i are the water demand and the pressure head of the i-th node respectively, Q_r and H_r are the water discharge and the total head of the generic r-th source point, and h_* the design pressure head of the network (i.e. the minimum required pressure to guarantee the minimum service level to the users).

The GA is computed with 100 generations for a population encompassing 50 individuals. Each individual is a sequence of binary chromosomes and have a length equal to the number of boundary links N_{ec}. Besides, each chromosome assumes a value 0 if a gate valve is inserted in the j-th pipe, and a value 1 if a flow meter is installed. The crossover percentage is set to P_{cross} = 0.8, and the mutation rate P_{mut} = 0.02. The objective function is constrained by the Equation (2).

$$h_{min} \geq h^* \qquad (2)$$

where h_{min} is the minimum nodal head pressure. This Equation (2) forces a minimum service level to the users. The process continues by selecting the optimal solution that minimises the number of flowmeters needed.

3.4 Decision Support System

Dynamic DMAs aid water utilities in their Decision Support System (DSS) for monitoring and controlling a WDS. Through the proposed dynamic DMA strategy, water utilities can consider other management tasks to achieve the following objectives:

- an economic criterion for selecting a final optimal solution between the set of configurations satisfying the hydraulic criteria;
- an optimal resilience index for the WDS;
- an optimal head pressure management to leakage control.

All these challenges are achieved by a further selection of WDS partitioning configurations that make use of the already installed devices. That is, there is no further need to buy new flow meters or gate valves, since the dynamic aggregation / disaggregation of the DMAs requires only to open and close valves. This strongly simplifies the management of unexpected, emergency scenarios. The overall process for the creation of Dynamic DMAs is summarised in Figure 1.

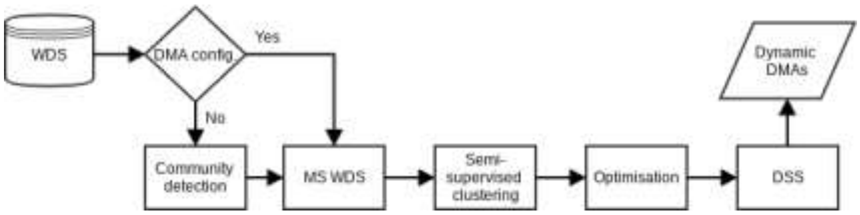


Fig. 1: Flowchart of the process for the creation of Dynamic DMAs

4 Experimental study

The creation of dynamic DMAs is tested for a real, medium-sized WDS by simulations of abnormal water demand. The aim is to show the performance of the dynamic DMAs on scenarios that worsens the hydraulic performance of the WDS. The novel dynamic WDS partitioning should ensure the optimal operation and management of the system while restoring the minimum service level for the users.

4.1 Case-study of Parete WDS

The proposed methodology is tested on the WDS serving the city of Parete,Italy (see Figure 2). Parete WDS currently supplies a population of more than 11,000 inhabitants. As Figure 3a shows, this network encompasses 182 junctions and 2 reservoirs, with fixed head of 110 m a.s.l, (n = 184 nodes), and 282 pipes (m = 282 links). Table 1 shows the hydraulic performance for the un-partitioned WDS. This performance can be considered as good in terms of the maximum h_{max}, mean h_{mean} and minimum h_{min} pressure head (higher than the design pressure head h^* = 19 m). A WNP is computed beforehand as aid for the system management and leakage control. In this respect, the WDS is partitioned into C = 9 DMAs as shown in the district layout in Figure 3a. The partitioning is based on the maximum day consumption in the year when the total nodal demand ranged from 7.6 L/s at night-time to 110.2 L/s during the morning and midday peaks, with an average value of 36.3 L/s. Table 1 reports the main topological and hydraulic characteristics of the WDS together with the simulation results. In such table I_b is the cluster balanced index which corresponds to the standard deviation in terms of how well the clusters are balanced with respect to their number of nodes. The cluster layout corresponding to 9$DMAs$ (p = 3.00) is well balanced, having an I_b = 4.45. The number of flow meters is low, N_{fm} = 13, considering that the number of boundary pipes is N_{fm} = 20. The hydraulic criteria are all satisfied as h_{max} = 50.27 m, h_{mean} = 28.23 m, h_{min} = 19.05 m and I_r = 0.369. The WDS has a good resilience index value. This represents a reduction of around 23% compared to the un-partitioned layout.

Fig. 2: Geographical location of Parete city

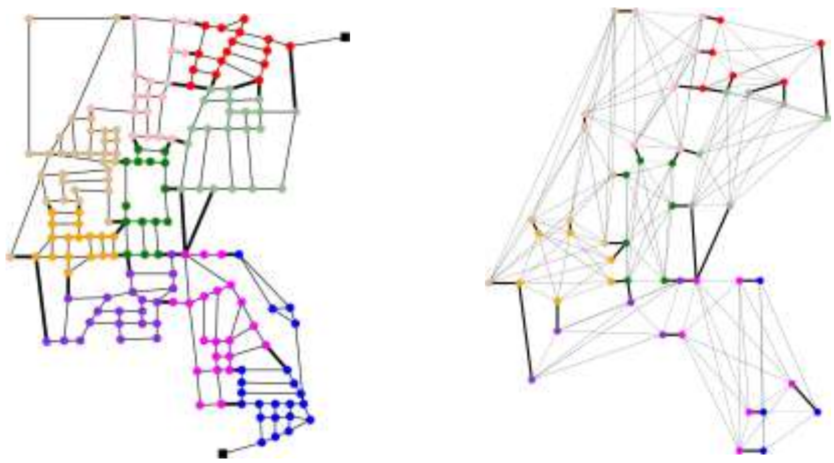
The experimental study continues by simulating an increase in the water demand, for the whole WDS, up to 15% during the midday peak. Without loss of generality, it is assumed that the water sources can meet such demand. This scenario leads to a severe decline in WDS performance; particularly, in its resilience. Under these conditions, the 9 DMAs partitioning do not satisfy the design criteria as described above (see 9*DMAs* (p = 3.45)).

The WDS is now characterised by a lower value of pressure head (h_{max} = 49.08 m, h_{mean} = 22.55 m, h_{min} = 10.87 m respectively) and a resilience index I_r = 0.168. This is a reduction of around 65% with respect to the un-partitioned layout, as Table 1 shows. The dynamic aggregation / disaggregation of DMAs is therefore proposed as a viable solution for managing such worsening in the WDS performance under abnormal water demand conditions.

4.2 Dynamic DMA configuration for Parete WDS

The dynamic DMA configuration first detects if a clustering layout of the WDS exists. This is done ahead of computing the corresponding MS network. Figure 3a shows the 9 DMAs of Parete WDS. Figure 3b shows the MS representation of the Parete WDS. That is, the boundary nodes, boundary links (bold black line) and the internal links (thin dashed grey line). The set of the MS-network hyper-links is crucial for automatically implementing the semi-supervised clustering at the DMA aggregation phase. The boundary links represent the connectivity between different clusters, while the internal links constitute the internal connectivity of each cluster (according to the shortest path linking each pairs of boundary nodes belonging to the same cluster).

A suitable number of clusters C is proposed in order to optimise the overall connectivity of the partitioned network. According to Giudicianni et al (2018), the optimal number of clusters is $C_{opt} \propto n^{0.28}$ from a topological point of



(a) DMA division for Parete WDS (b) MS Parete WDS

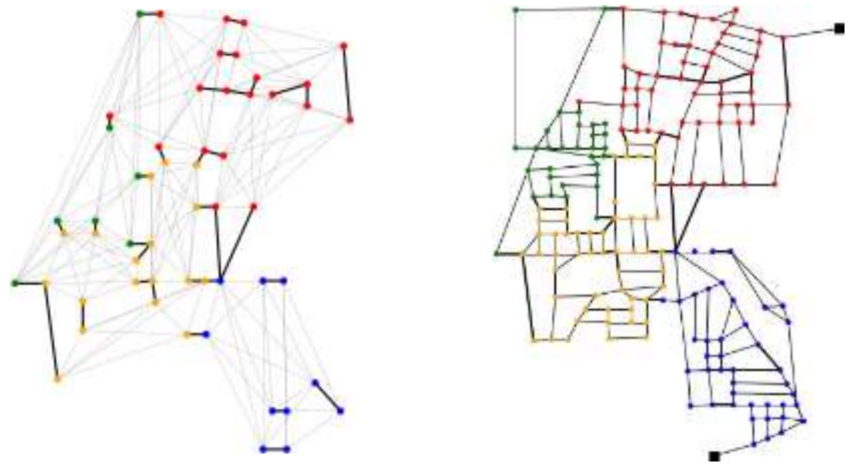
Fig. 3: Graphical explanation for the creation of Parete MS WDS layout (9 DMAs)

view. Consequently, the new number of clusters for Parete is set to $C = 4$ (see Figure 4a).

The first step to creating the dynamic DMAs is to represent the previous, smaller DMAs into an MS network, satisfying all the criteria associated with the semi-supervised clustering. Then, the Girvan-Newman algorithm is applied, to the MS network to get a new clustering layout which suitably balances the new, bigger 4 DMAs in size and minimises the number of boundary links between clusters. Another important aspect to highlight is that the application of the clustering phase on the MS network drastically reduced the computational time for the DMA aggregation phase since the complexity of the community structure algorithms is proportional to the number of nodes n, which is necessary lower in the MS representation than in the original WDS. Figure 4b shows that the 4 new, bigger clusters perfectly include the former DMAs (avoiding splitting them), and so the new DMA configuration follows an internal continuity. The new DMAs are well balanced (as listed in Table 1, I_b = 9.72) and the new set of boundary links $N_{e}^{*}{}_{c}$ = 14 constitutes a subset of the previous set N_{ec} = 33 (i.e. all the new boundary links for C = 4 DMAs are also boundary links for the case of C = 9 DMAs, Figure 4a).

This represents the most important point of the dynamic aggregation / disaggregation phase since it ensures that the DMAs in each phase are in control, while the process makes use of the assets already installed in the WDS. Finally, it is important to note that it is possible to reverse to the original layout of the WDS at any time.

After the definition of the new clustering layout, the boundary links inside the new 4 bigger DMAs are opened (4*DMAs* (p = 3.45) layout) and the



(a) DMA aggregation over MS Parete WDS (b) DMA division for Parete WDS

Fig. 4: Graphical explanation for the creation of Parete MS WDS layout (4 DMAs)

Table 1: Topological and hydraulic characteristics of the original un-partitioned WDS, of the network partitioned in C=9 DMAs during normal midday peak, of the network partitioned in C=9 DMAs during the abnormal midday peak, and of the network partitioned in C=4 DMAs during the abnormal midday peak for Parete WDS.

Layout	N_{ec}	N_{fm}	N_{gv}	I_b	h_{min}	h_{mean}	h_{max}	I_r
	[-]	[-]	[-]	[-]	[m]	[m]	[m]	[-]
Un-partitioned	-	-	-	-	21.36	31.05	50.47	0.481
9 DMAs (p=3.00)	33	13	20	4.45	19.05	28.23	50.27	0.369
9 DMAs (p=3.45)	33	13	20	4.45	10.87	22.55	49.08	0.168
	N^*_{ec}	N^*_{fm}	N^*_{gv}	I_b	h_{min}	h_{mean}	h_{max}	I_r
	[-]	[-]	[-]	[-]	[m]	[m]	[m]	[-]
4 DMAs (p=3.45)	14	5	9	9.72	16.21	25.61	48.93	0.274
4 DMAs (p=3.45)-GA	14	7	7	9.72	17.56	25.98	49.24	0.303

hydraulic performance checked. This step ensures the simplification of the aggregation / disaggregation phase management. If the minimum service level is not yet satisfied (as it happens in this case, Table 1, for which h_{min} = 16.21 m and the resilience index is I_r = 0.274), a dividing phase, along with a GA optimisation for Equation (1), is applied to the new DMA configuration.

The solutions that use the already installed flowmeters on the WDS are chosen, out of all the possible optimal solutions, for further consideration at the DSS stage.

Hence, the economic adequacy of the solution is assured, since all the existing assets are reused and only the installation of the strictly necessary additional flowmeters is required. The DSS in Figure 5 shows a maximum number

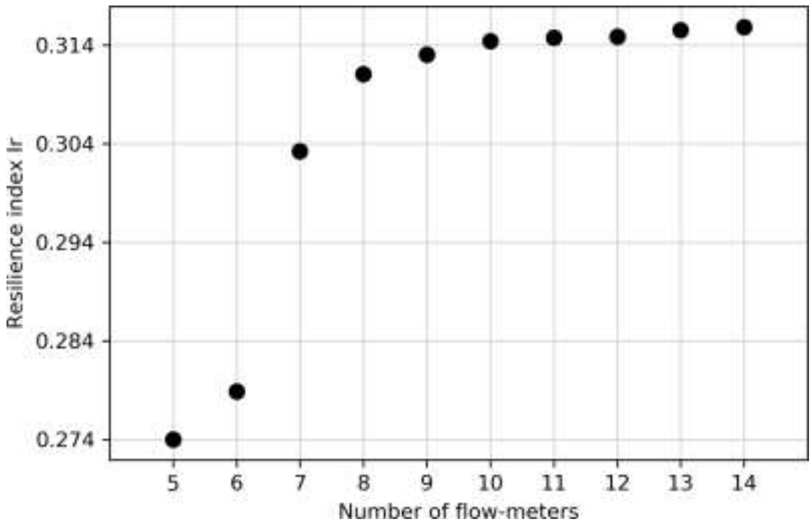


Fig. 5: Decision Support System for the optimal partitioning layout of Parete WDS

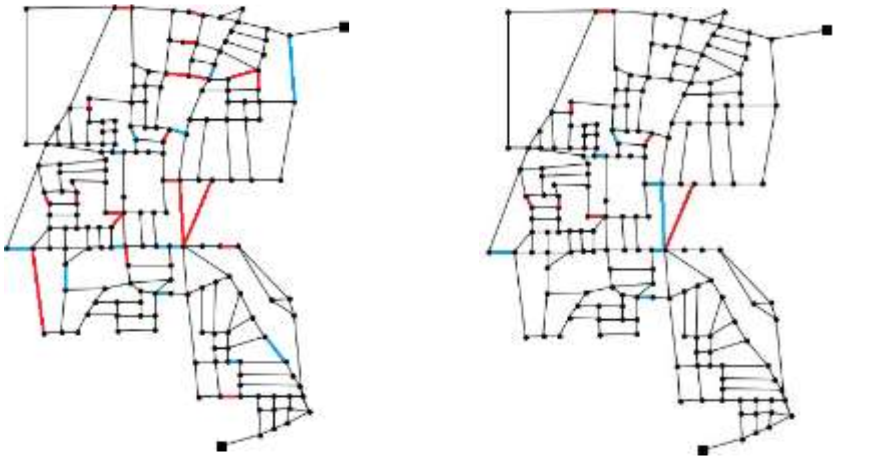
of 14 flowmeters for the new aggregated layout (a flowmeter per each boundary pipe) and a minimum of 5 flow-meters, 4*DMAs* (p = 3.45).

The solution with 7 flow meters and 7 gate valves is the most suitable configuration for the case study, as the simulation results (Table 1), show better resilience index. That is, the 4*DMAs* (p = 3.45) $\_$ *ttA* solution is restored (I_r = 0.303, just 17% less than the original partitioned layout 9*DMAs*(p = 3.00), and 4% less than the resilience of the virtual partitioning with N^*_{fm} = 14). The minimum pressure h_{min} = 17.56 m is slightly lower than h^* = 19 m, but only 9 nodes do not satisfy the pressure constraint.

Figure 6 shows the two partitioning layouts; Figure 6a shows the initial partitioning in 9 DMAs and Figure 6b shows the best solution composed by 4 bigger DMAs after the optimisation phase. It is evident that all the boundary pipes of the new partitioning layout constitute a sub-set of the previous boundary pipe set. In addition, five of the seven installed flowmeters are the same as those already installed for the partitioning in 9 DMAs (blue lines). This means that, it is possible to restore the performance of the WDS by using 94% of the devices already installed; requiringonly two new flow meters to are added.

5 Conclusions

Most cities have an existing water distribution systems (WDSs) with assets of different deterioration grade and performance capacity. WDSs are alsoprone



(a) 9 DMAs (b) 4 DMAs

Fig. 6: Optimal partitioning layout for Parete WDS; red lines for gate-valves and blue lines for flow-meters

to changes in demand due to variation in user behaviour, population size or industrialisation. Their assets are also exposed to failures due their own degradation or external factors. This poses risks to the WDS, affecting its performance, operation and reliability. However, a WDS does not necessarily have the same risk level at all its geographic areas and issues affecting water supply such as pipe bursts, may have a local rather than a global effect. A WDS partition into district metered areas (DMAs) is a widely used strategy for leakage control, to facilitate WDS operation and management and to increase the overall network resilience. This makes it possible to work with each DMA depending on its individual physical and hydraulic characteristics. The inherent variability on the customers criticality at each DMA, from hospitals and schools to domestic areas and industrial water use, makes it necessary to propose specific water management strategies per area.

This paper investigates the potential to dynamically, and automatically, partition WDSs in response to a range of abnormal events. Specifically, the paper analyses the impact of an increase in peak water demand as an abnormal, not-contemplated, condition for a water utility.

The main novelty presented is the methodology development for such dynamic partitioning into DMAs. This is approached by an also novel multiscale (MS) representation of the WDS, based on key components of the original layout, combining their topological features with advances in network modelling and optimisation. The MS representation is used to create dynamic DMAs within existing physical and hydraulic constraints. The new network re-configuration simplifies the top-down / bottom-up clustering, while preserving the set of boundary pipes, and other assets, at each level. As an additional finding, the MS network reduces the computational burden associated with the water network partitioning (WNP) problem, since the reduced dimensionality of the MS representation is based on a subset of the original layout. This makes the MS approach particularly suitable for large WDSs management and visualisation.

The proposed dynamic DMAs approach is tested on the water utility network of Parete (Italy). The results show the efficiency of dynamic DMAs on providing an optimal, sustainable solution which simultaneously ensures the restoration of the hydraulic performance when the city faces an unprecedented increase in the water demand. The dynamic DMAs strategy for Parete WDS also reduces the investment cost of a new partitioning reconfiguration. The problem of the increased peak demand addressed in this paper also stresses the importance of considering the spatio-temporal variability of water demand during the definition of the optimal WNP. This has been shown that just an increase of 15% in the water demand sharply deteriorates the performance of the whole system. All the solutions provided by the novel dynamic DMA framework balances the cluster size and minimises the number of boundary links. The dynamic DMA also guarantees to maintain a minimum service level. In addition, this also has the benefit of being a low-cost partitioning layout, since it is based on already installed WDS components, avoiding the need to reconfigure the entire network and the installation of additional assets.

Future work will address the automatic reconfiguration of the dynamic DMAs at sectorial or partial network level. That is, to aggregate DMAs of a certain sub-area of the WDS while the rest of the DMAs may remain unchanged. This will help to take preventive and mitigation actions for abnormal conditions such as contamination , (multiple) pipe failure, extreme weather events, and firefighting. The aim is to also extend the MS dynamic DMA framework into self-regulated dynamic DMAs which face seasonal and foreseen water issues affecting the whole WDS and unexpected, global and local, undesirable events.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

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